

# COMPARATIVE CHARACTERIZATION OF DIETARY FIBRE-ENRICHED FROZEN/THAWED MASHED POTATOES

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*The potential use of commercial fibres (pea fibre, inulin, and their blends), as fibre-enriching agents in frozen/thawed mashed potatoes was reported. Pea fibre and inulin supplementations conferred hardness and softness to the product, respectively. Differences were attributed to the relationship of the fibre with the potato starch matrix. The association of pea fibre at low concentration (<15 g/kg mashed potatoes) and inulin at high concentration (>45 g/kg) is strongly encouraged to fortify the diet without promoting negative effects on textural and rheological properties of frozen/thawed mashed potatoes or colour and overall acceptability of the resulting products.*

**Keywords:** *Dietary fibre, Mashed potatoes quality, Oscillatory test, Rheology, Microstructure.*

## INTRODUCTION

The health benefits of fibre consumption are well recognized. A diet with low dietary fibre is associated with a spectrum of degenerative diseases, including diabetes, obesity, coronary heart disease, bowel cancer, and gallstones; it is a well-established fact that the consumption of adequate amounts of dietary fibre significantly reduces the risk of these diseases.<sup>[1]</sup> Consumer awareness of these characteristics is increasing; this influences consumer purchasing decisions, while the functional foods market is constantly growing. A recent joint FAO/WHO report recommended reducing the intake of sugars, fat, and alcohol, and increasing consumption of fruits, vegetables, and cereal products, with the aim of increasing the total dietary fibre intake to at least 25 g day<sup>-1</sup>.<sup>[2,3]</sup> The challenge is to develop traditional mashed potatoes using dietary fibres to increase the daily intake of fibres.

Dietary fibre is a collective term for a group of substances of varying chemical composition, structure, physical properties, and physiological effects.<sup>[4]</sup> A final agreement was only reached in November 2008 on a global dietary fibre definition for the Codex Alimentarius.<sup>[5]</sup> Now the Codex defines dietary fibre as carbohydrate polymers with 10 or more monomeric units, which are not hydrolysed by the endogenous enzymes in the small

intestine of humans. Such an agreed definition facilitates consistent application of labeling and health claims, thus, ensuring clarity and enhancing consumer confidence.<sup>[4]</sup>

Nowadays, a whole range of fibres are available in the market, but sometimes it is difficult to choose properly because of the variation in their physicochemical properties. Numerous fibres from completely different sources have been isolated and characterized and incorporated into different food products.<sup>[6]</sup> In fact, there are now many fibre-enriched products on the market.<sup>[7]</sup> Fibres have been incorporated in a wide variety of foods, like dairy products,<sup>[8–12]</sup> meat, or fish,<sup>[13,14]</sup> but bakery products are the preferred source of dietary fibre.<sup>[1,3,4,6,15–18]</sup> However, there are few references to mashed potatoes with added dietary fibres. Nonetheless, some fibres obtained from algae, like carrageenans, or produced by *Xanthomonas campestris*, like xanthan gum, have been used for technological purposes in mashed potatoes.<sup>[19,20]</sup> The greatest improvement in overall acceptability (OA) of frozen/thawed mashed (F/TM) potatoes has been achieved by the addition of kappa-carrageenan ( $\kappa$ -C) and xanthan gum (XG) (each hydrocolloid at 1.5 g/kg); the improvement of F/TM potato texture was ascribed to the retarding of starch retrogradation, increased water binding capacity, and enhancement of the principal characteristics determining consumer acceptance.<sup>[21]</sup>

Bearing in mind the necessity of increasing dietary fibre ingestion (especially in Western societies) and that customers demand not only healthier foods but also high sensory quality,<sup>[15]</sup> this research work was mainly focused on the possibility of offering F/TM potatoes with improved nutritional value and with high consumer acceptability. This work includes a systematic study on the effect of fibres of different origins—insoluble (pea fibre) and soluble (inulin) dietary fibres, added singly (PF and I, respectively) and in associated blends (PFI)—on the textural and rheological properties and the microstructure of processed mashed potatoes. Thus, colour, total soluble solids content, and OA of the above samples were investigated to evaluate the product's appearance and make consumer-acceptable fibre-enriched F/TM potatoes.

## MATERIAL AND METHODS

### Materials

The potatoes used were tubers (*Solanum tuberosum*, L., cv Kennebec) from Aguilar de Campoo (Palencia, Spain). PF (Vitacel<sup>®</sup> Pea Fibre EF 150, J. Rettenmaier & Sohne GmbH & Co., Rosenberg, Germany) was an insoluble fibre with a total dietary fibre content ~70 g/100 g (dry matter), of which was insoluble dietary fibre content  $\geq 65$  g/100 g, soluble dietary fibre content  $\geq 0.5$  g/100 g, and resistant starch content  $\geq 1.5$  g/100 g, according to producer's data. Inulin (I) (Orafti<sup>®</sup> HP, BENEIO-Orafti, Tienen, Belgium) was a "long-chain" I with a degree of polymerization, DP (total number of fructose or glucose units)  $> 23$  and purity of 99.5% (producer's data).  $\kappa$ -C (GENULACTA carrageenan type LP-60) and XG (Keltrol F [E]) were donated by Premium Ingredients, S.L. (Girona, Spain). Following range finding experiments, the lower and upper fibre levels to be used were set at 0 and 45 g/kg for PF alone and at 0 and 60 g/kg for either I alone or PFI blends. Concentrations and codes used for identification of samples are shown in Table 1.

### Preparation of F/TM Potatoes

Tubers were manually washed, peeled, and diced. All mashed potatoes were prepared in ~1350-g batches from 607.7 g/kg of potatoes, 230.8 g/kg of semi-skimmed in-bottle

**Table 1** Concentrations and codes used for identification of samples at each fibre type. Effect of fibres type and average values of instrumental measurements and sensory score for the F/TM potatoes.

	Source of variation	BEF (N)	CPF (N/g)	$\delta$ (°)	G' (Pa)	G'' (Pa)	$\eta_{app,50}$ (Pa s)	n	K (Pa s <sup>n</sup> )
PF (g/kg)	C1: 0								
	C2: 15								
	C3: 30								
	C4: 45								
I (g/kg)	Fibres type								
	PF	8.11 <sup>a</sup>	2.24 <sup>a</sup>	15.22 <sup>a</sup>	6103.06 <sup>a</sup>	1581.40 <sup>a</sup>	5.54 <sup>a</sup>	0.20 <sup>a</sup>	132.11 <sup>a</sup>
	I	5.14 <sup>b</sup>	1.76 <sup>b</sup>	18.17 <sup>b</sup>	3278.90 <sup>b</sup>	1063.38 <sup>b</sup>	4.98 <sup>a</sup>	0.26 <sup>a</sup>	87.50 <sup>b</sup>
	PFI	5.52 <sup>b</sup>	2.28 <sup>a</sup>	15.14 <sup>a</sup>	5857.86 <sup>a</sup>	1525.27 <sup>a</sup>	5.03 <sup>a</sup>	0.20 <sup>a</sup>	111.58 <sup>a</sup>
	P values	<0.001	<0.001	<0.001	<0.001	0.0012	0.4475	0.067	<0.001
	F-ratios	22.20	11.31	15.02	10.72	7.52	0.83	4.11	14.77
TSS [g/100g (w/w)]									
PFI (PF + D) (g/kg)		YI	$\Delta E^*$		OA				
	C1: 0								
	C2: 10 PF + 30 I								
	C3: 30 PF + 10 I								
	Fibres type								
	PF	14.53 <sup>a</sup>	1.94 <sup>a,b</sup>	12.09 <sup>a</sup>	3.73 <sup>a</sup>				
	I	12.44 <sup>b</sup>	2.58 <sup>a</sup>	14.96 <sup>b</sup>	7.29 <sup>b</sup>				
	C5: 15 PF + 45 I								
	C6: 45 PF + 15 I								
	C7: 30 PF + 30 I								
	P values	<0.001	<0.001	<0.001	<0.001				
	F-ratios	19.43	9.57	10.48	12.73				

<sup>a,b</sup>: For each variable, mean values without the same letter are significantly different ( $P < 0.01$ ).

sterilised milk (fat content,  $15.5 \text{ g kg}^{-1}$ ),  $153.8 \text{ g/kg}$  of water,  $7.7 \text{ g/kg}$  of salt (NaCl), and  $1.5 \text{ g/kg}$  of either  $\kappa$ -C or XG<sup>21</sup> using a TM 31 food processor (Vorwerk España, M.S.L., S.C., Madrid, Spain). I (concentration  $0\text{--}60 \text{ g/kg}$ ) was previously dissolved in  $384.6 \text{ g/kg}$  of water and milk at  $70^\circ\text{C}$  for 15 min, stirring constantly with a magnetic stirrer. The ingredients were first cooked for 30 min at  $90^\circ\text{C}$  (blade speed:  $0.10 \times g$ ). The amount of liquid evaporated was determined by weighing the ingredients before and after first cooking. This liquid was then replaced by adding milk. In terms of processability, there were serious difficulties in cooking PF fibre together the rest of the ingredients, especially in cases where PF levels exceeded  $15 \text{ g/kg}$ . PF (concentration  $0\text{--}45 \text{ g/kg}$ ) was previously hydrated at a ratio of PF to water of 1:6, and then also added at this point. Next, all the ingredients were cooked for an additional 5 min at  $90^\circ\text{C}$ . The mash was immediately ground for 40 s (blade speed:  $80 \times g$ ), 20 s (blade speed:  $450 \times g$ ), and 20 s (blade speed:  $1000 \times g$ ), and then homogenized through a stainless steel sieve (diameter 1.5 mm). Following preparation, mashed potatoes were placed on flat freezing and microwave thawing trays and then frozen by forced convection with liquid nitrogen vapour in an Instron (Canton, MA, USA) programmable chamber (model 3119-05;  $-70/+250^\circ\text{C}$ ) at  $-60^\circ\text{C}$  until their thermal centres reached  $-24^\circ\text{C}$ . After freezing, samples were packed in polyethylene plastic bags, sealed under light vacuum ( $-0.05 \text{ MPa}$ ) on a Multivac packing machine (Sepp Haggemüller KG, Wolfertschwenden, Germany), placed in a domestic freezer for storage at  $-24^\circ\text{C}$ , and left there for at least 1 month before thawing to assure the appropriate experimental repeatability of the freezing and frozen storage processes. Packed frozen samples were thawed in a Samsung M1712N microwave oven (Samsung Electronics S.A., Madrid, Spain). Samples were heated for a total of 20 min at an output power rating of 600 W, as detailed elsewhere.<sup>[22]</sup> After thawing, the temperature reached at the product thermal centre was measured in all cases ( $+50 \pm 5^\circ\text{C}$ ). All samples were brought up to  $55^\circ\text{C}$  by placing them in a Hetofrig CB60VS water-bath (Heto Lab Equipment A/S, Birkerød, Denmark). Sample testing temperature was  $55^\circ\text{C}$ .<sup>[22]</sup>

### **Instrumental Textural Properties**

Back extrusion (BE) and cone penetration (CP) tests were performed using a TA.HDPlus Texture Analyser (Stable Micro Systems Ltd., Godalming, UK) equipped with a 300 N load cell. For performance of BE tests, a rig (model A/BE, Stable Micro Systems) was used consisting of a flat 45 mm diameter Perspex disc plunger that moved within a 50 mm inner diameter Perspex cylinder sample holder containing  $50 \pm 1 \text{ g}$  of mashed potatoes. The product was extruded to a distance of 20 mm at  $2 \text{ mm/s}$  compression rate. Maximum positive force of extrusion (firmness (N), BEF) was recorded. For performing the CP tests, a TTC spreadability rig (model HDP/SR, Stable Micro Systems) was used consisting of a  $45^\circ$  conical perspex probe (P/45 C) that penetrated a conical sample holder containing  $7 \pm 0.1 \text{ g}$  of product. The product was penetrated to a distance of 17.5 mm at a  $3 \text{ mm/s}$  compression rate. Maximum force of penetration per gram of product (firmness (N/g), CPF) was recorded. Texture measurements were performed in quadruplicate and the results averaged.

### **Oscillatory and Steady Rheological Measurements**

A Bohlin CVR 50 controlled stress rheometer (Bohlin Instruments Ltd., Cirencester, Gloucestershire, UK) was used to conduct small amplitude oscillatory shear experiments and steady shear using a plate-plate sensor system with a 2 mm gap (PP40, 40 mm) and

a solvent trap to minimize moisture loss during tests. Before measurements were taken, samples were left between the plates for 5 min equilibration time.<sup>[21]</sup> Temperature control at 55°C was achieved with a Peltier Plate system (−40 to +180°C; Bohlin Instruments). Dynamic rheological tests were performed under the following conditions: (1) linear viscoelastic domain determined for each sample from stress sweeps at 1 rad/s, and (2) three frequency sweeps over the range 0.1–100 rad/s. The applied stress was selected to guarantee the existence of linear viscoelastic response according to previous stress sweeps carried out. A new sample was used each time for rheological measurements, which are, therefore, average values of four determinations. Values of phase angle ( $\delta$ , deg), storage modulus ( $G'$ , Pa), and loss modulus ( $G''$ , Pa) were recorded at 1 rad/s. Flow curves were obtained at shear rates of 0.1–100 1/s approximately, which is the range of interest in food texture studies.<sup>[23]</sup> Viscosity values in the upward viscosity/shear rate curves at a shear rate of 50 1/s ( $\eta_{app,50}$ , Pa s) were taken as the apparent viscosity of the samples. Data were also fitted to the Ostwald de Waele model,<sup>[24–26]</sup> where  $n$  is the flow behaviour index and  $K$  (Pa s <sup>$n$</sup> ) is the consistency index.

**Other quality parameters** Instrumental measurement of colour of the F/TM potatoes in the pots was carried out with a HunterLab model D25 (Reston, VA, USA) colour difference meter fitted with a 5 cm diameter aperture.<sup>[27,28]</sup> Results were expressed in accordance with the CIELAB system with reference to illuminant D65 and a visual angle of 10°. A colour index, the yellowness index (YI), was calculated as  $142.86b^*/L^*$ .<sup>[27]</sup> The total colour difference ( $\Delta E^*$ ) between respective controls made without added fibres (C1 concentrations, Table 1) and the rest of F/TM samples made with the corresponding added fibres was calculated as follows:

$$\Delta E^* = \left[ \left( \frac{L_n^* - L_1^*}{K_L S_L} \right)^2 + \left( \frac{C_n^* - C_1^*}{K_C S_C} \right)^2 + \left( \frac{H_n^* - H_1^*}{K_H S_H} \right)^2 \right]^{1/2}$$

where  $L_1^*$ ,  $C_1^*$ , and  $H_1^*$  are the reference (fresh sample) colour parameter values and  $S_L = 1.0$ ,  $S_C = 1 + 0.045C_1^*$ , and  $S_H = 1 + 0.015C_1^*$ .  $K_L$ ,  $K_C$ , and  $K_H$  are parametric factors and vary with the experimental conditions. All were given a fixed unit value for the combination of our specific reference conditions.<sup>[18,19]</sup> Total soluble solids (TSS) content [g/100g (w/w)] as measured by refractive index was determined with an Atago (Itabashi-ku, Tokyo, Japan) dbx-30 refractometer. Measurements of colour and TSS content were performed in quadruplicate and the results averaged.

**Sensory analysis** Sensory assessment was conducted by a 14-member untrained panel. F/TM potatoes were subjected to an overall acceptability (OA) test based on all sensory attributes (texture, colour, taste), on a nine-point hedonic scale (with 8 cm) labeled at each anchor (left anchor: 1 = dislike extremely; right anchor: 9 = like extremely).

### Scanning Electron Microscopy (SEM)

F/TM potato microstructure was examined by SEM using a Hitachi model S-2.100 microscope (Hitachi, Ltd., Japan), National Center for Metallurgical Research (CENIM-CSIC). Mashed potato samples were air-dried then mounted on metal holders, followed by gold sputter-coating (200 Å approx.) in a SPI diode sputtering device. Photomicrographs were taken at various magnifications with a digital system Scanvision 1.2 of Röntgenanalysen-Technik (800 × 1.200 pixel, Rontec, GmbH, Berlin, Germany).

## Statistical Analyses

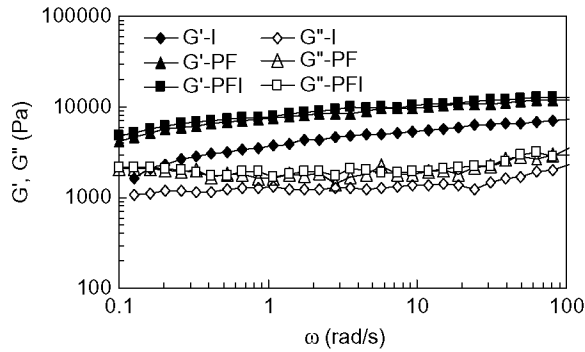
A one-way ANOVA was applied to evaluate how fibre types (PF and I) and blends (PFI) affected the textural and rheological properties, colour parameters, TSS content, and the OA of the F/TM potatoes. Linear discriminant analysis (LDA) was performed to focus on the possible objective discrimination between the different types of fibres incorporated into the samples on the basis of their quality attributes. One-way ANOVA were applied to each fibre type (PF, I, and PFI blends) to evaluate how the concentration of each fibre by itself or of blends of these (Table 1) affected the above mentioned quality parameters of the products. Minimum significant differences were calculated using Fisher's least significant difference tests with a 99% confidence interval for the comparison of instrumental parameters, and a 95% confidence interval for comparison of OA. Statistical analyses were performed with Statgraphics® software version 5.0 (STSC Inc., Rockville, MD, USA).

## RESULTS AND DISCUSSION

### Effect of Fibre Types and Blends on Instrumental Measurements and OA of F/TM Potatoes

For comparative analysis of the influence of the two insoluble and soluble dietary fibres (PF and I, respectively) and their binary blends (PFI) on the BEEF, CPF,  $\delta$ ,  $G'$ ,  $G''$ ,  $\eta_{app,50}$ ,  $n$ ,  $K$ , YI,  $\Delta E^*$ , and TSS values and the OA scores of the F/TM potatoes, an ANOVA of one factor was performed (Table 1). One can see that the samples with only soluble fibre (I) presented significantly lower CPF,  $G'$ ,  $G''$ ,  $K$ , and YI values and higher  $\delta$  values and OA scores than their counterparts with either added PF alone or PFI blends. None of the samples differed statistically in the values of apparent viscosity and  $n$  index. With regard to consumer acceptance, long-chain I can act as a fat mimetic thanks to its capacity to form microcrystals, which interact with each other to form small aggregates that occlude a large amount of water; this creates a fine and creamy texture that gives a mouthfeel similar to that of fat.<sup>[8,9]</sup> In contrast, the lowest water absorption was found with the addition of I to wheat flour.<sup>[16]</sup>

According to their mechanical spectra (Fig. 1), the response of samples with both 30 g/kg added I or PF alone, or those containing 30 g/kg of each fibre (C7 blend, Table 1), was typical of a cross-linked polymer network;<sup>[11]</sup> i.e., the storage modulus  $G'$  was higher than the loss modulus  $G''$  at any given frequency, which is a characteristic of viscoelastic solids. The shape of the rheological spectrum was similar for all the other samples. It is worth noting the effect of I addition taking into account the samples with PF incorporation. The addition of any I concentration produced a softening of the structure, and in the samples with added I alone there was slightly higher frequency dependence (particularly at low frequency) with a more significant drop in  $G'$  values than in  $G''$  values. This result shows that the addition of I conferred different blending properties on the F/TM potatoes, surely due to the fructose polysaccharides in its composition.<sup>[16]</sup> One of the possible mechanisms by which I increased the phase angle—which gives a relative measure of the energy lost versus energy stored in the cyclic deformation (a  $\delta$  of 90° indicates the material is fully viscous)—is the presence of small I particles.<sup>[29]</sup> Such small particles can be produced by controlling heating and cooling of the dissolved I to induce nucleation and, thus, small insoluble crystal formation.<sup>[30]</sup> The presence of I has been reported to facilitate the reduction of snack bar hardness,<sup>[4]</sup> and a negative effect of I has also been observed, making mackerel surimi gels softer when incorporated at 40 g/kg, whereas PF increased



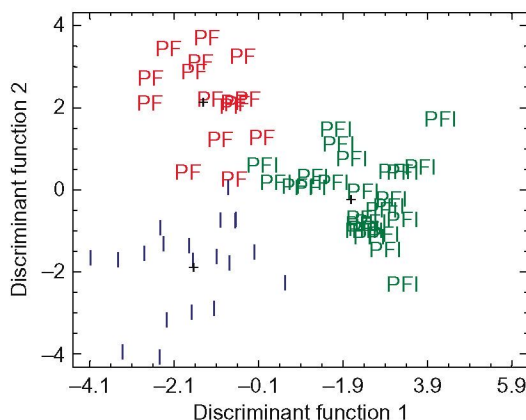
**Figure 1** Mechanical spectra of samples containing 30 g/kg of PF alone, 30 g/kg of I alone, and a blend of 30 g/kg of PF and I fibres.

hardness (an increase of almost 60% with 40 g/kg).<sup>[14]</sup> Furthermore, other studies have shown that incorporation of low levels ( $\leq 40$  g/kg) of inner PF and chicory root I may alter the texture of restructured fish products, i.e., inner PF fibre favoured greater gel strength and hardness,<sup>[13]</sup> whereas I fibre reduced hardness.

With regard to YI index, commercially available I is a spray-dried white powder that gives an opaque gel at higher concentrations when mixed properly with water.<sup>[31]</sup> This whitish powder and the opaque gel made from it reduced the yellowness and increased the  $\Delta E^*$  of the samples (Table 1). In addition, the TSS content increased when I was added either alone or in associated blends. Supplementation with I introduced some more reducing sugars and led to increased total carbohydrate contents.<sup>[10]</sup> The same behaviour was observed in dairy drinks with added oligofructose<sup>[11]</sup> and I,<sup>[8]</sup> respectively.

In contrast, no significant differences in CPF,  $\delta$ ,  $G'$ ,  $G''$ , and  $K$  values were detected between samples with added PF alone and with added PFI blends (Table 1, Fig. 1). Therefore, the presence of insoluble fibre increased the firmness per gram, elasticity, viscosity, and consistency of the samples, evidencing that I is unable to counteract the effect produced by the high proportion of cellulose present in PF fibre. This is likely due to interactions between the fibre structure and the water. In wheat dough, the highest water absorption was found with the addition of PF, followed by carob fibre.<sup>[16]</sup> Note, however, that firmness (BEF value) increased when PF was added alone, whereas PF addition in associated blends left BEF basically unchanged as compared to the addition of I alone. The apparent lack of correlation between the two types of textural measurements (BEF and CPF per gram) indicates that both parameters are measuring different effects in the matrix of the F/TM potatoes. According to Lee and Chung,<sup>[32]</sup> while the compression test measures the overall binding property of the gel material, the penetration test evaluates the degree of compactness. If we accept this interpretation, PF considerably increased either overall binding or the degree of compactness in the mashed potato gel network, but the presence of I considerably reduced overall binding and the structure of the gel became weaker. In addition, other authors have reported that at very high I concentrations both potato starch and I probably gel independently, with potato starch remaining in the amorphous state<sup>[33]</sup> and I recrystallizing.<sup>[34]</sup>

In spite of the fact that ANOVA confirmed that there was little variability between some of the instrumental measurements of F/TM potatoes formulated with either added



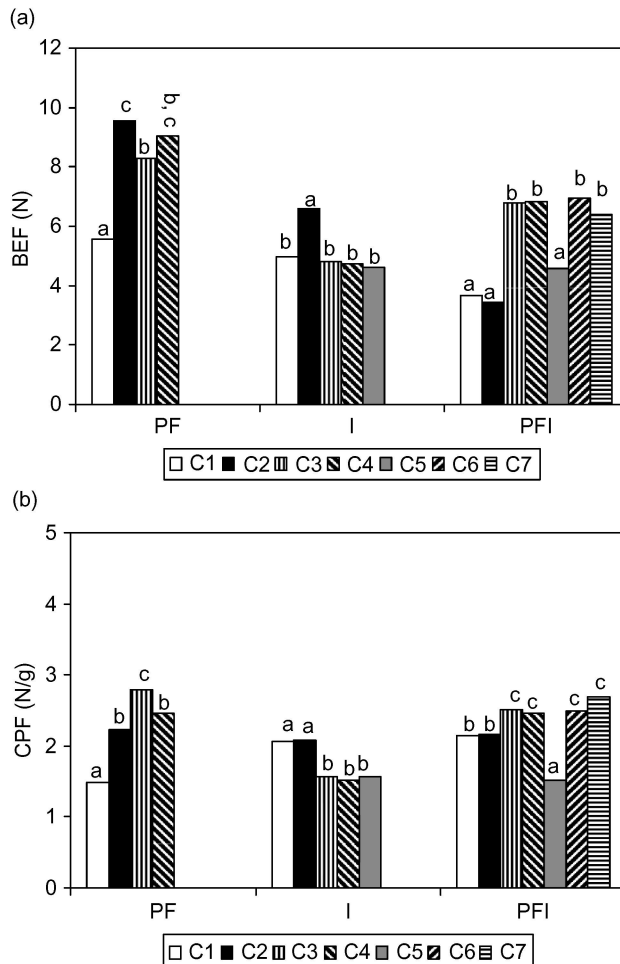
**Figure 2** Plot of observations on the two principal axes obtained via LDA based on addition of PF, I, and PFI blends as the discriminating factor. (Color figure available online.)

PF alone or PFI blends, LDA using fibre type as the discriminant factor showed that the three samples type investigated were clearly discriminated. LDA was performed to develop two functions to discriminate between the two types of fibre and their blends based on linear combinations of the 12 quality attributes shown in Table 1. The relative percentages of variance accounting for discriminating functions 1 and 2 were quite similar (59 and 41%, respectively) indicating that none of the functions on its own can discriminate well between the three levels of the factor. The standardized coefficients of the functions used to discriminate amongst the types of fibre are not shown for the sake of brevity. However, for the first discriminant function, YI and TSS content are clearly the attributes that best separate the PF, I, and PFI samples, whereas for the second function, BEF,  $G''$ , and OA are the attributes that best separate the samples by fibre content. Figure 2 shows the projections of the observations onto the two axes extracted by the LDA. There appears to be a clear discrimination between samples with both added PF and I alone or their blends. However, average values (group centroids) of the two discriminant functions for each of the three fibre types are included in Fig. 2; they are marked by a small plus sign. Centroid values show that function 1 discriminates mainly between F/TM samples with added PFI blends and those with either PF or I alone (it separates them by more than 3 units). Note that the first function hardly discriminates between samples with either added PF or I alone. On the other hand, function 2 discriminates mainly between samples with added PF alone and those with added I alone (it separates them by more than 4 units), albeit the second function also discriminates quite well between samples with added PFI blends and those with either added PF or I alone (it separates them by more than 2 and 1 unit, respectively). These results indicate that the addition of both fibres and their blends appears to interfere with the structure of F/TM potatoes differently.

### Effect of Fibres Concentration on Quality Attributes of F/TM Potatoes

To study the influence of the concentration on the quality attributes and the OA scores of the F/TM potatoes, three different one-way analyses were performed on each fibre type and blends of these. Figures 3 and 4 show the effect of fibre concentration on the textural (BEF and CPF) and rheological properties ( $\delta$ ,  $G'$ ,  $G''$ ,  $\eta_{app,50}$ ,  $n$ , and  $K$ ) of F/TM potatoes





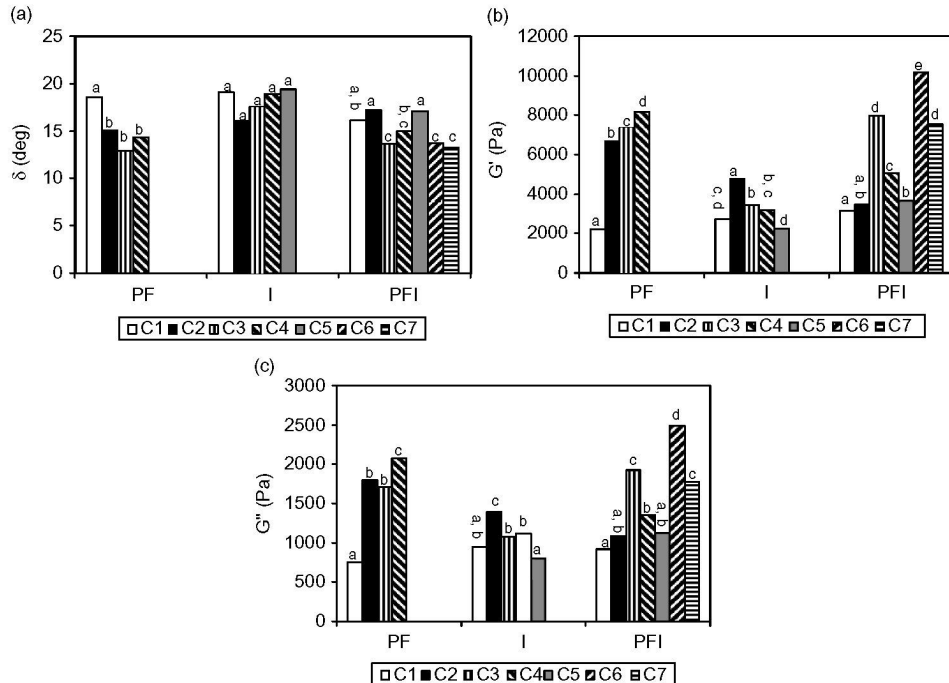
**Figure 3** Textural and rheological properties of F/TM potatoes: (a) back extrusion firmness; (b) cone penetration firmness per gram.

with either PF or I added alone or PFI blends. In terms of texture and oscillatory dynamic measurements, fibre concentration significantly affected ( $P \leq 0.01$ ) the majority of these properties. Only in the case of the  $\delta$  value (Fig. 4a) as a function of concentration was there no significant change in F/TM potatoes with added I alone.

In F/TM samples, adding 15–45 g/kg PF alone (C2–C4 concentrations respectively; Table 1) increased both BEF (Fig. 3a) and CPF (Fig. 3b) properties as compared to mashed potatoes without added PF fibre (C1 concentration). These results indicate that much stronger structures are produced when F/TM potatoes contain insoluble fibre. The maximum BEF and CPF values were recorded in samples containing 15 and 30 g/kg, respectively, albeit differences in BEF and CPF values between samples with 15 and 45 g/kg added PF were not significant. With regard to I addition, the highest BEF value was recorded in the samples containing 15 g/kg I. There were no significant differences either in BEF values for I at 30–60 g/kg or in CPF for I at 15 g/kg (Fig. 3b) compared with their control (C1), whereas adding higher levels of I (30–60 g/kg) significantly reduced the CPF values of the samples.

With regard to the addition of PFI blends, there were no significant differences in the BEF values of the samples with added C2 and C5 blends (both with  $\leq 15$  g/kg added PF, Table 1) and the C1 control without fibre. The variation in the CPF value (Fig. 3b) shows that firmness per gram was lowest in the samples with added C5 blend (which had the lowest (15 g/kg) and the highest (45 g/kg) PF and I contents, respectively), even lower than in the C1 control. Furthermore, samples with higher PF concentrations (C4, C5, C6, and C7 blends) had higher BEF and CPF values than C1 control, albeit differences between samples were not significant. The texture measurements show that firmness tended to increase with PF content and decrease with I content, except in the case of the BEF value with the lower level of I (Fig. 3a). Results show that the texture tests did not adequately discriminate the changes in sample structure produced by the fibre addition. In the case of the PF fibre, this effect may have been due to deficient wetting of the fibres at the higher concentrations because of their high water holding capacity, and also to the formation of clusters owing to the relative length of the pea fibres.<sup>[1]</sup>

Samples with added PF had lower  $\delta$  values (Fig. 4a), indicating greater elasticity, although differences between phase angles of F/TM potatoes with added PF alone were not significant. Conversely, the effect of the concentration was linear and elasticity ( $G'$  values) increased at the three concentrations used (Fig. 4b). In the samples with added I, the effect of the concentration was also linear, with  $\delta$  increasing and  $G'$  decreasing at the four test concentrations tested. Nevertheless, there were non-significant differences between  $\delta$  values due to greater dispersion of the results; also, the samples containing 15 and 30 g/kg I were more elastic than the control. This fact is probably related to I

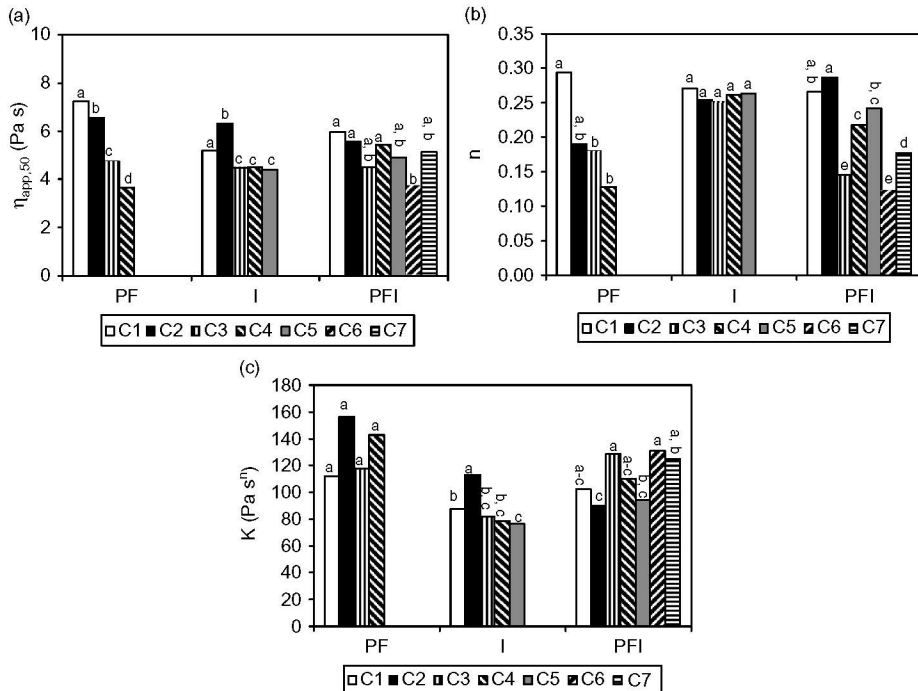


**Figure 4** Oscillatory rheological properties of F/TM potatoes: (a) phase angle; (b) storage modulus; (c) loss modulus.

low concentration, as the system does not have enough particles and/or molecular density of I chains to reach a critical crowding effect.<sup>[35]</sup> For their part, samples with added C3, C6, and C7 blends, all with  $\geq 30$  g/kg added PF, had significantly lower  $\delta$  values than the control (Fig. 4a), indicating that high levels of PF favoured lower viscosity.<sup>[36]</sup>  $G'$  increased when any of the PFI blends studied was added, and only the samples formulated with the blend containing the lowest PF concentration (C2) had similar elasticity to the control (Fig. 4b). On the other hand, F/TM potatoes with added C6 blend containing the highest PF concentration exhibited the greatest elasticity with a higher magnitude of  $G'$ , followed by samples containing 30 g/kg added PF (C3 and C7 blends).

With respect to the viscosity of the samples (Fig. 4c), the maximum loss modulus  $G''$  was likewise recorded with the highest level of PF added alone. Addition of the highest I concentration (C5, 60 g/kg) reduced the viscosity, albeit differences with control were non-significant. Again, the maximum  $G''$  value was recorded in samples containing 15 g/kg I. The changes in the values of  $G''$  on adding PFI blends were similar to those observed in elasticity (Fig. 4b). In addition, no significant differences were found in the viscous properties of the samples without added fibres and those with added C2 and C5 blends (with lower PF contents and with 30 and 45 g/kg I, respectively).

Steady shear measurements: the effect of concentration on the consistency index ( $K$ ) was not significant for samples with added PF alone (Fig. 5c). There was no significant change in the  $n$  index (Fig. 5b) as a function of concentration in F/TM potatoes with added I alone. Concentration likewise had no significant effect ( $P \leq 0.01$ )  $\eta_{app,50}$  (Fig. 5a) and



**Figure 5** Steady rheological properties of F/TM potatoes: (a) apparent viscosity; (b) flow behaviour index; (c) consistency index.

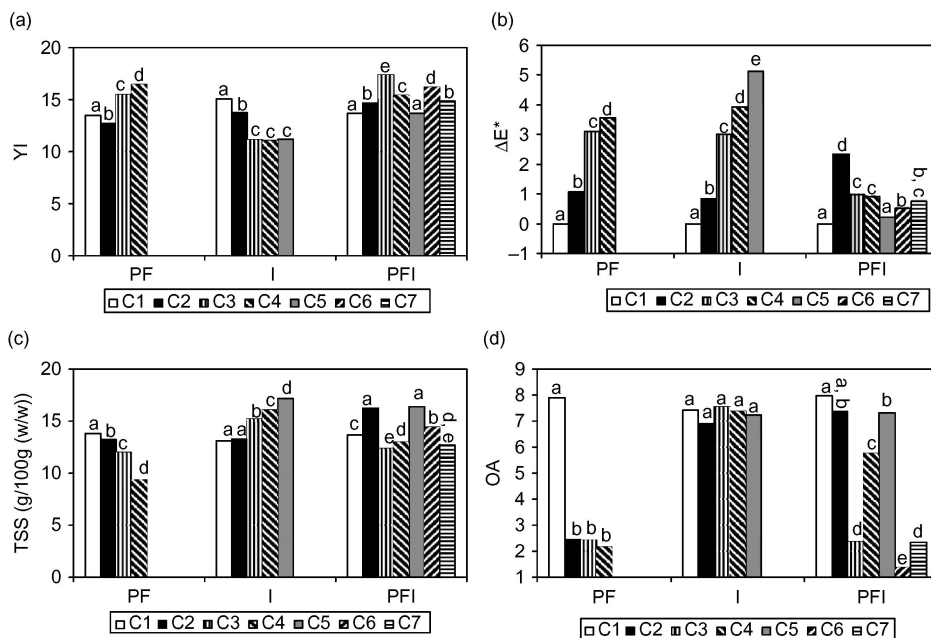
$K$  (Fig. 5c) in F/TM potatoes with added PFI blends. In F/TM samples with added PF alone, the effect of the concentration was linear, with  $\eta_{app,50}$  decreasing (Fig. 5a) at the three concentrations used. The  $n$  index, which indicates the extent to which shear-thinning deviates from 1, was also reduced by adding 45 g/kg (Fig. 5b), although in this case the pseudoplasticity of samples containing lower PF concentrations (15 and 30 g/kg) was not significantly lower than in the samples containing 45 g/kg I.

With regard to I addition, the maximum  $\eta_{app,50}$  and  $K$  values were recorded in samples containing 15 g/kg I. Addition of the highest I concentration (C5, 60 g/kg) also significantly reduced consistency (Fig. 5b). Only the addition of I at 15 g/kg increased apparent viscosity (Fig. 5a), whereas the  $\eta_{app,50}$  of the samples with 30, 45, and 60 g/kg was similar but significantly lower than in the control. In the former case, there are various hypotheses that could explain this behaviour. According to Zimeri and Kokini,<sup>[37]</sup> it could be due to the fact that the structure of I has no entanglements at all, with agglomerates (crystals) sliding one on top of the other. The latter authors also indicated that the rheological properties of mixed I-waxy maize starch (WMS) systems at ratios of I to WMS of 50:50 presented a decrease in the moduli's magnitude due to WMS network disruption by I, when compared to gels with lower I concentrations. Several studies have addressed mixed carbohydrate interactions, and it has been found that their miscibility in solution decreases with increasing concentration.

Addition of PFI blends: the analysis of variance showed that the effect of the different concentrations of fibres on both  $\eta_{app,50}$  and  $K$  was only significant at the 0.05 level. In fact, unexpectedly, all the samples with added PFI blends had lower apparent viscosity than the control (Fig. 5a); however, when 45 g/kg of PF and 15 g/kg of I (C6) was added, the  $\eta_{app,50}$  value decreased significantly with respect to the C1 control, indicating that addition of a high PF concentration produced a slight weakening of the initial structure of the system. With respect to the flow index ( $n$ ) (Fig. 5b), on increasing the PF concentration and reducing the I concentration (C3, C4, C6, and C7 blends), the  $n$  value decreased, although the increase in pseudoplasticity was greater in the flow of the samples with the lower I concentrations. Similarly, the lowest sample consistency was recorded for the F/TM potatoes with added C2 blend, indicating that in the presence of a low PF content the addition of 30 g/kg of I caused slight softening of the original structure of the system. At PF concentrations above 30 g/kg, on the other hand, such addition increased sample consistency although the differences with the control were not significant. Note that in the presence of PF fibre there was no correlation between the  $\eta_{app,50}$  and  $K$  values, which may be attributed to early fixing of the structure and a high level of water in the product. These results are in disagreement with those reported by Fernández et al.<sup>[20]</sup> after adding five different hydrocolloids and two dairy proteins to mashed potatoes. The high correlation between  $\eta_{app,50}$  and  $K$  was associated with the presence of a shift from a viscoelastic regime to a purely viscous one as found for selected gum solutions,<sup>[38]</sup> since  $K$  is the shear stress at a shear rate of  $1.0 \text{ s}^{-1}$ . In contrast, when applying extensional rheometry at large strain deformations, Piteira et al.<sup>[1]</sup> observed that PF incorporation in cookie dough did not seem to affect the dough's uniaxial transient flow at strains above approximately 0.1. On the contrary, between approximately 0.01 and 0.1 strain units, the transient extensional viscosity seems to decrease the more is incorporated. Also, it has been reported that both mixing tolerance index and elasticity were reduced by the addition of PF to wheat dough.<sup>[16]</sup> Moreover, the extensibility of the dough and the deformation energy were greatly reduced by PF, yielding a reduction of about 42% in the extensibility of the wheat flour and, hence, a smaller bubble before

failure, probably due to the high cellulose content in this fibre. Thurston and Pope<sup>[39]</sup> suggested that the decrease in the viscous component at a high shear rate reflects loss of the ability of compounds to store elastic energy in the shear deformation process. A similar absence of correlation between small and large deformation tests has been reported for other gels.<sup>[14]</sup>

Figure 6 shows the effect of fibre concentration on colour parameters, TSS content and OA of F/TM potatoes with PF or I added alone or PFI blends. In general terms, when added singly or in associated blends, fibre content significantly affected ( $P \leq 0.01$ ) both the colour parameters and the TSS content of the samples. Only in the case of F/TM potatoes with I added alone was there no significant change in OA score as a function of concentration. In samples with added PF alone, adding the lowest level of PF slightly reduced the YI value as compared with control (Fig. 6a). Conversely, yellowness increased significantly when 30 and 45 g/kg PF was added. Cod sausages have also been reported to become yellower with pea protein.<sup>[40]</sup> In samples with I added alone, adding 15–60 g/kg I reduced the YI value as compared with the control, although there was no significant difference in the yellowness of the different mashed potatoes formulated with higher I concentrations (30–60 g/kg). Conversely, it has been found that I did not affect the colour values of low-fat ice cream.<sup>[41]</sup> And again, addition of oligofructose to dairy drinks did not affect the  $L^*$ ,  $a^*$ , and  $b^*$  values.<sup>[11]</sup> Obviously, the colour of the ingredients used influences the colour of the product. The PF ingredient was a brown powder, and the F/TM potatoes with added PF were darker brown in colour, whereas the samples without PF were yellower in colour. In fact adding increasing levels of PF increased both  $L^*$  and  $b^*$  values, and as a result, the F/TM potatoes with added PF fibre were darker (lower  $L^*/b^*$  ratio) than the C1 control.



**Figure 6** Quality attributes and OA of F/TM potatoes: (a) yellowness; (b) colour difference; (c) total soluble solids; (d) overall acceptability.

On the other hand, I is a white powder and produced a lighter-coloured mashed potato (higher  $L^*/b^*$  ratio) than the control, reducing the YI value. In the case of blend addition, all samples except the ones with the lowest PF content (C5) had significantly higher YI values than the control (Fig. 6a), indicating that the darkening produced by PF addition was stronger than the lightening caused by I incorporation. Curiously, as Fig. 6b shows, the value of  $\Delta E^*$  (the reference taken in the three cases was the colour of the respective C1 controls) increased linearly when the concentration of either PF or I increased. Comparison of the total colour differences suggests that the addition of the same concentration of either fibre alone to F/TM potatoes affected the final colour in the same way, albeit PF and I caused samples to darken and brighten, respectively. In samples with added PFI blends, the value of  $\Delta E^*$  with respect to the C1 control was much higher at the lowest PF concentration (C2 blend, Table 1), suggesting that in this case the lightening caused by I addition masked the effect of PF addition.

TSS content decreased linearly with PF content (Fig 6c). PF contains mostly insoluble fibre with high water absorption and some soluble solids may be hard to detect. However, as was expected, total soluble solids were higher in samples containing I than in the control, which agrees with the findings reported by other authors<sup>[11]</sup> in probiotic yogurts supplemented with fructo-oligosaccharide. Also, in the case of the addition of blends, those samples with lower PF concentrations and higher I contents (C2 and C5) had higher TSS contents.

Sensory characteristics are influenced by microstructure. The addition of PF fibre reduced the OA score of the F/TM potatoes (Fig. 6d), whereas Wang et al.<sup>[16]</sup> found that breads containing PF were judged acceptable by the panellists. In this study, panellists preferred F/TM potatoes without added PF. There was no difference ( $P \geq 0.05$ ) in the average scores of samples containing PF fibre, indicating that the different pea fibre concentrations used did not interfere in the acceptability of the samples. Scores were noticeably lower in these cases, probably due to the considerable differences in texture, colour, flavour and odour of these samples as result of the original properties of the PF fibre. The undesirable effect of fibre on bread consists mainly of an objectionable gritty texture and unsuitable taste and mouthfeel.<sup>[7]</sup> In fact, PF significantly influenced sample texture, which was perceived as sandy because of the high proportion of cellulose. Also, PF increased perceived hardness when added to F/TM potatoes either alone or at the maximum tested levels. The sensory analysis indicates that PF alone cannot be used as an ingredient in mashed potatoes to fortify the diet. There were no significant differences in OA scores for F/TM potatoes without and with added I at any concentration. Unlike other reports,<sup>[8,12]</sup> there was no clear relationship between the sensory score and the quantity of soluble fibre added individually, which is likely related to the presence of XG in all the systems. The addition of XG at any of the concentrations used, either individually or blended with  $\kappa$ -C, increased the creaminess of F/TM potatoes.<sup>[21]</sup> However, several reports also corroborate the influence of I on such mouthfeel parameters as creaminess and thickness. The addition of I to low-fat and whole milk set yoghurt influences the perception of creaminess. With rising I concentration, the perception of creaminess increases as well.<sup>[12]</sup> Also, milk-beverage model systems with added I were perceived as significantly creamier than samples without I.<sup>[8]</sup> With respect to the interval of concentrations considered in this work, incorporation of 15–60 g/kg I did not significantly affect the perceived creaminess and mouthfeel of the products, and the resulting texture were perceived as smoother.

The variation in the OA score for PFI blends indicates that with the lowest PF concentration and I at 30 g/kg (C2 blend), consumer acceptance was comparable to control

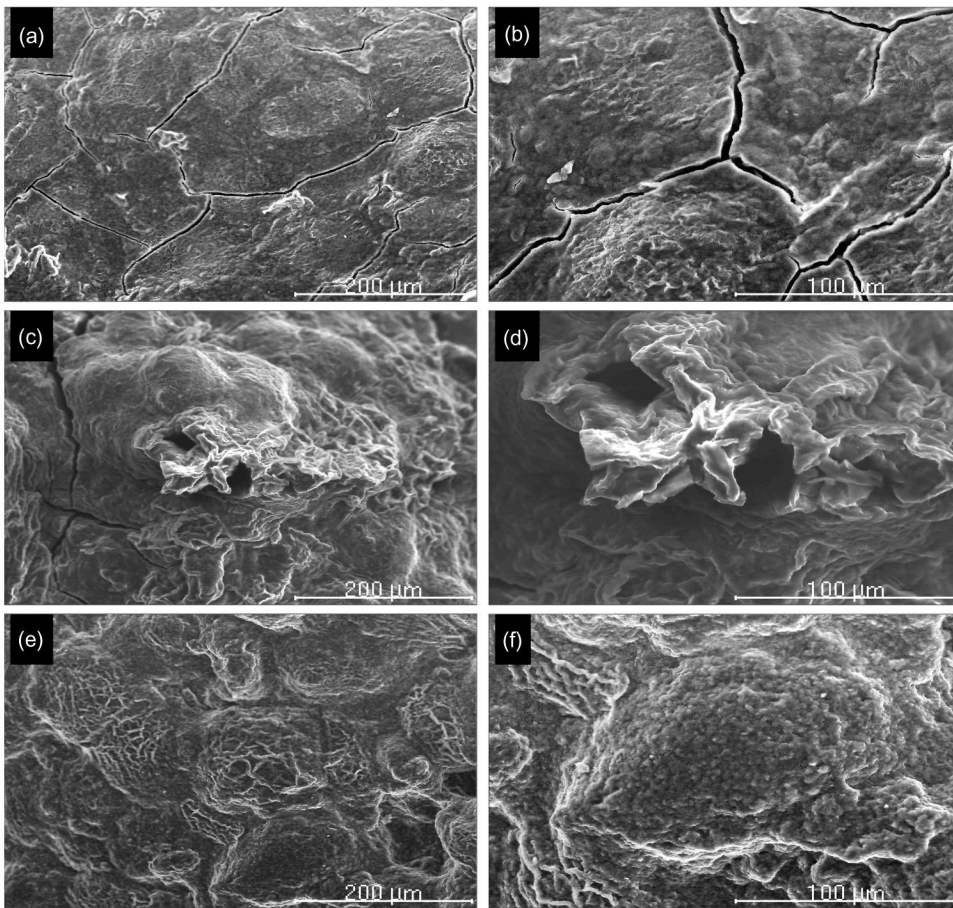
without added ingredients. Also, samples with 15 g/kg added PF and 45 g/kg added I (C5 blend) were judged by the consumer panelists as very acceptable, scoring >7 for OA (Fig. 5d). Therefore, the association of both fibres at minimum levels of PF and maximum levels of I largely counteracted the hardening effect of addition of PF alone. On the other hand, samples supplemented with binary blends containing  $\geq 30$  g/kg PF (C3, C6, and C7 blends) scored considerably less than those with 10 and 15 g/kg addition.

## SEM

Microstructure was analysed by SEM (Figs. 7 and 8). The photomicrographs in Figs. 7b, 7d, 7f, 8b, 8d, and 8f show close-up views of each sample. Those F/TM potatoes containing PF alone exhibited clear differences. When food and other biomaterials are frozen, the expansion associated with phase changes and subsequent contraction due to further cooling will cause mechanical stresses to develop, which may cause deformation and large-scale cracking or micro-structural damage. This topic has been relatively neglected in the food literature, but it was clearly visible in all the samples formulated with PF alone either at low (Figs. 7a and 7b) or at high concentrations (Figs. 7c and 7d). Kim and Hung<sup>[42]</sup> suggested that the propensity to crack in liquid nitrogen immersion freezing depends on several interrelated physical properties such as the porosity and frozen density of the food. Density influences cracking because it is proportional to moisture content, and products with higher moisture content will have a higher volume expansion ratio during freezing and hence higher cracking susceptibility. In this study moisture contents were not measured, but it is definitely probable that the F/TM samples with added PF alone had higher moisture content than the other samples,<sup>[14,34]</sup> especially given that these samples contained more water in order to assure hydration of PF fibre.

In this study drip loss after centrifugation was always zero in all samples; this fact is attributed to the presence of XG in the systems, indicating that the water binding capacity of the F/TM potatoes containing this gum was absolute.<sup>[21]</sup> However, in their respective counterparts without added cryoprotectants (data are not shown), the presence of PF increased water binding capacity as compared to I. Similarly, water absorption in wheat dough was highest when PF was added.<sup>[16]</sup> This is likely caused by the large number of hydroxyl groups in the PF fibre structure, which allow more water interactions through hydrogen bonding. Therefore, F/TM potatoes with PF added alone are more rigid (as evidenced by instrumental measurements), have more moisture content, and have no or very little expansion due to phase change; this would create extremely high tangential tensile stress at the surface<sup>[42]</sup> as the inner layers freeze and expand, stretching the rigid outer crust. Thus, cracking is unlikely to occur during thawing.<sup>[43]</sup> It is possible, however, that in the products with high PF content, the cracks that have formed and propagated during freezing will continue towards the centre during thawing and complete the splitting process, especially given the limited water available and restriction of water movement during thawing of the products, which is quickly entrapped by the PF fibre. Unlike PF, I incorporation did not cause cracking (Figs. 7e and 7f), and in the case of samples with added PFI blends, some cracking was only detectable (Fig. 8b) with the lowest I concentration (C3 blend, Table 1). The higher the I content, the greater is the chance that internal stress will dissipate instead of accumulating. This is probably related to that fact that I incorporation increases porosity.

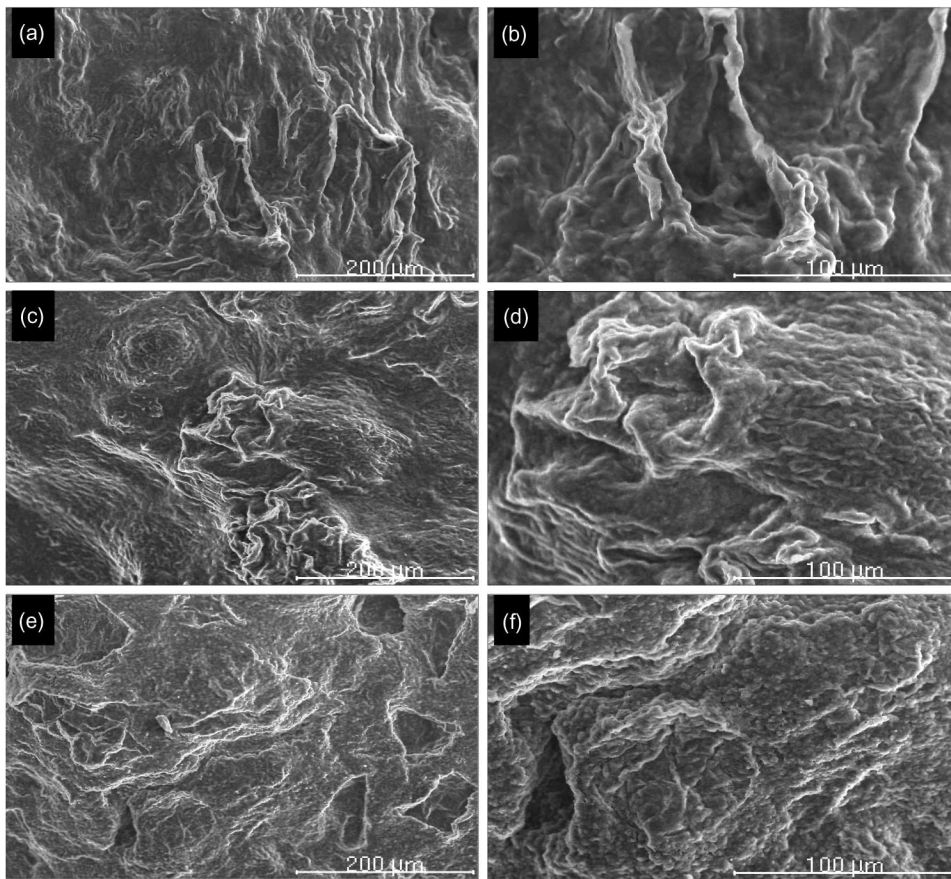
F/TM samples consisted mainly of whole single potato cells and of some ruptured cells and cell fragments embedded in an extracellular starch phase, which was blended with



**Figure 7** Scanning electron photomicrographs of F/TM potatoes: (a) and (b) with 15 g/kg added PF; (c) and (d) with 45 g/kg added PF; (e) and (f) with 60 g/kg added I.

gelled  $\kappa$ -C and XG. This gum was effective in stabilizing F/TM potatoes against starch retrogradation, minimizing the spongy structure formation of frozen gel.<sup>[44]</sup> Samples with 15 g/kg added PF (Figs. 7a and 7b) present a more dehydrated appearance, since part of the intracellular water was drawn out osmotically when the product was frozen because of freezing-induced concentration of the cell mass. Moreover, these samples seemed to present some whitish brands, which were most obvious in the samples containing higher PF concentrations either alone (Figs. 7c and 7d) or blended with I (Figs. 8a–8d). The addition of PF to the product appeared to disrupt the continuity of the potato starch matrix, producing a microstructural arrangement, undulating surfaces (Figs. 7c, 8a, and 8c) and, unlike other reports,<sup>[14,18]</sup> a more compact morphology. A close examination of the samples with added PF at quite a high concentration also revealed the formation of wrinkles, ridges, and folds (Figs. 7d, 8b, and 8d). Macromolecules show a preference for being surrounded by their own type in mixed solutions, and consequently self-association is intensified in the presence of other macromolecules.<sup>[3]</sup> F/TM potato microstructure is explained by dietary fibre composition, and PF contains insoluble polysaccharides.<sup>[14]</sup> The texture of the mashed





**Figure 8** Scanning electron photomicrographs of F/TM potatoes: (a) and (b) with 30 g/kg added PF and 10 g/kg added I; (c) and (d) with 20 g/kg added PF and 20 g/kg added I; (e) and (f) with 15 g/kg added PF and 45 g/kg added I.

potatoes was possibly reinforced by interactions between the PF's polysaccharides—i.e., insoluble dietary fibre forming a cellulose-rich backbone structure—and starch.<sup>[16]</sup> Photomicrographs of the F/TM potatoes with 30 g/kg added PF and 10 g/kg added I show the PF-potato starch matrix to be well formed, with strong, continuous fibre strands entrapping some starch granules (Figs. 8a and 8b).

However, even though it is not easy to differentiate I from potato starch granules, samples with 60 g/kg added I (Figs. 6e and 6f) and with 15 g/kg added PF and 45 g/kg added I (Figs. 7e and 7f) all had an I-rich phase with small I crystallites forming a continuous network. These crystallites are hard to make out when I content is lower (Fig. 7d). At 45 and 60 g/kg, I presented a microstructure formed by clusters of small I crystals. In the case of added I fibre, the I-potato starch matrix was more continuous than in the samples containing PF, confirming previous findings.<sup>[18]</sup> The magnitude of the overall textural and rheological properties of these samples decreased, due mainly to the integration of I crystals in a developed potato starch network; this in turn resulted in a smoother texture, which can probably be explained by the correlation between the presence of I crystals and

the development of gelling properties of I. This reinforces the hypothesis of an I gelation mechanism proposed in other scientific papers.<sup>[29,31,35]</sup> Figs. 6f and 7f also confirm the hypothesis of Zimeri and Kokini.<sup>[37]</sup> These authors stated that I's structure is formed by agglomerates (crystals), with no interconnections with one another. Reduction of hardness of pasta has been reported with increasing I concentration,<sup>[18]</sup> associated with the way in which the I was incorporated into the structure of the pasta. And again, the starch granules in pastas containing soluble dietary fibre appeared to be coated in a mucilaginous-like layer.<sup>[3]</sup>

## CONCLUSIONS

F/TM potato quality was determined by means of texture, colour, and TSS content. The rheological behaviour of the F/TM potatoes was studied by means of oscillatory and steady measurements, establishing the influence of fibre type on the OA of F/TM potatoes. The original colour of the ingredients clearly influenced the colour of F/TM potatoes. Oscillatory dynamic tests proved more sensitive than steady, back extrusion, and penetration tests. Thus,  $G'$  and  $G''$  were found to be suitable to describe the change in F/TM potato structure in terms of differences in the behaviour of the products as a function of fibre type concentration. LDA showed that YI and TSS content are the attributes which best separate samples enriched with either PF or I and PFI-enriched samples, whereas BEF,  $G''$ , and OA are the attributes that best distinguish the samples with PF and I when added singly. Results show that F/TM potato texture, structure and potential sensorial quality are intrinsically linked to the integration of fibre in F/TM potatoes systems. Major differences in structure may be related to the solubility of the fibre added. In particular, PF (mainly insoluble) and I (soluble) fibres show marked differences in their potential to affect the OA of the products. These differences may be attributed to the behaviour of the fibre within the system and the relationship of the fibre with the potato starch matrix. This study appears to confirm that the addition of insoluble PF to mashed potatoes causes disruption and cracking of the potato starch matrix, and consequently hardening. Conversely, the addition of soluble I fibre results in the entrapment of small I crystals within a soft I-potato starch network.

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